

## **Annual Report for Ocean Acoustics**

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### **LONG-TERM GOALS**

One of the long-term goals of this project is to analyze and propose energy-efficient communication techniques for underwater acoustic sensor networks. These techniques aim at consuming as less energy as possible as well as guaranteeing a minimum quality of service. In order to do so, we assume and validate some statistics of the underwater acoustic channels and derive stochastic optimal transmission policies.

Another long-term goal of this project is to investigate the possibility that these underwater acoustic networks disrupt the behavior of surrounding species of marine mammals. As a consequence of these two studies, we aim at developing minimally disruptive communication schemes.

### **OBJECTIVES**

In order to develop the optimal controller that minimizes energy consumption in underwater acoustic communications, we identified the following intermediate objectives:

1. Develop a system model and an optimal transmission scheduler that minimizes the number of transmission attempts in the case where a given amount of packets,  $B$  have to be transmitted by a deadline,  $T$ . In this case the controller only decides whether or not it is convenient to transmit at a given time.
2. Include in the previous model the cost of transmitting feedback.
3. Include in the optimal controller, as control variable, other communication parameters such as transmission power and redundancy allocation.
4. Analyze the suitability and accuracy of the stochastic model for the underwater acoustic channel assumed in the stochastic optimal controller.
5. Analyze the sensitivity of the proposed solutions to environment-driven non-stationary statistics of the underwater acoustic channel.
6. Propose technical solutions to overcome possible performance degradation of the controller due to changes in the channel statistics.

In order to investigate the possibility that underwater acoustic communications disrupt behaviors of surrounding marine mammals, we identified the following objectives:

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- a. Identify a species that is sensitive to the same frequency ranges used for communications.
- b. Quantify the amount of information exchanged among 2 or more animals in different contexts, e.g., while foraging, diving, swimming and in different scenarios, e.g., where there are different social bounds and hierarchies.
- c. Investigate how they cope with multi-user (and artificial communication signals) interference while vocalizing.

## APPROACH

In order to derive optimal stochastic control policies, we make use of the dynamic programming algorithm, which requires to define a dynamic system model, whose evolution depends on both a random process, in our case the channel quality, and a control variable. At each stage, there is a cost associated to the current state and control variable, which is additive with time. The optimization consists in finding the set (called policy) of values of the control variable that minimizes the average total cost of the system evolution. Since we analyze the scenario where a finite number of packets has to be delivered by a deadline  $T$ , we only consider the finite-horizon problem. This can be achieved by applying the dynamic programming algorithm. Since such algorithm requires a prior knowledge on the statistics of the random process, we make use of a parametric stochastic model, such as Markov models, to represent the dynamics of the communication performance in time-varying underwater acoustic channels. We plan to validate the suitability of such model, and quantify the sensitivity of such approach. In order to do so, we make use of existing numerical acoustic propagation methods, e.g. Vertex, feed these methods with different environmental conditions (by using oceanographic models), and we perform a statistical analysis on the computed time series of channel impulse responses. After having identified the impacts of each different environmental condition on both the dynamics and features of the channel impulse response, a classifier at the receiver could be used in order to select the most suitable receiving signal processor, which then guarantees the assumed statistics for the communication performance, used by the controller.

By interacting with both bioacousticians and the marine mammal behavioral biologists at WHOI, Saint Andrews University, Duke University, and Scripps, we identified pilot whales as a species of interest in our studies, for the following reasons: i) their communication signals belong to the same frequency bands as that used in artificial acoustic communications, ii) these animals are highly social and use communications to coordinate with each other and maintain network connectivity, iii) they use deep dives ( $\sim 300$ -500 m) and in the past such deep divers have been proved to be negatively affected by sonar signals (e.g., mass strandings of Cuvier's beaked whales after sonar operations), iv) numerous data sets containing communication sessions among these animals have been already collected, recently. We tackle the problem of quantifying the information content in a communication session among two or more animals by considering the data sets collected by Prof. Peter Tyack, Dr. Laela Saiygh, and Dr. Frants Jesent, through DTags on long-finned pilot whales in Spain in 2010, 2011, and 2012. These data sets are particularly useful since a small group of related animals was tagged simultaneously and therefore it is easier to reconstruct a communication session, i.e., which animal transmits signals and which receives. This can be done by the comparing the signal amplitude at simultaneous recordings in different tags. From these reconstructed communication sessions, we can quantify metrics, such as network throughput, for different functional contexts (feeding, diving) and social boundings (mum-calf, mum-calf and associated adult, adult-adult). Moreover, by cross-correlating the transmitted and received signals at different tags, we can estimate the arrival time of

each message and quantify the interference at each animal, and start investigating their interference management technique.

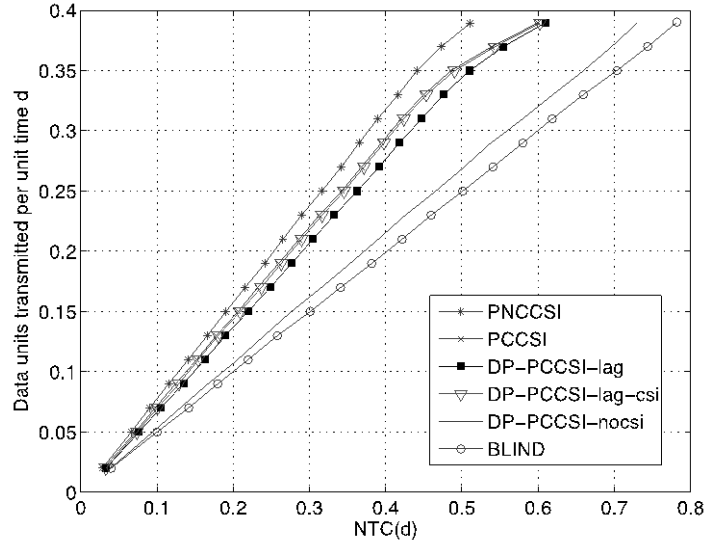
## WORK COMPLETED

The PIs started to work on this project on February 27, 2013. Up to the current date (September 30, 2013), a system model for determining the transmission scheduling that minimizes the number of transmission attempts was developed, and the dynamic programming solutions were derived. In such a model we consider a delayed channel state information that is available only when a transmission occurs. We also consider the cost of feeding this channel state information back and develop a controller that minimizes the number of both transmission attempts and CSI feedbacks at different system parameters. In particular, we consider different values for the channel statistics, the number of packets, and the deadline  $T$ . A manuscript with the obtained results is in preparation. Therefore, points 1 and 2 in the Objectives session are completed. The PIs have also started to tackle points 3 and 4.

The PIs have also started to analyze the data sets on Pilot whales, and in particular the communication session collected in 2010 where two tagged animals were performing an unsynchronized dive. In the ascending part, the diving animal was sending messages to the animal close to the surface, which returned with a series of vocalizations. The task in point *a*, indicated in Objective, was completed, and the PIs are now advancing with points *b* and *c* in the Objectives.

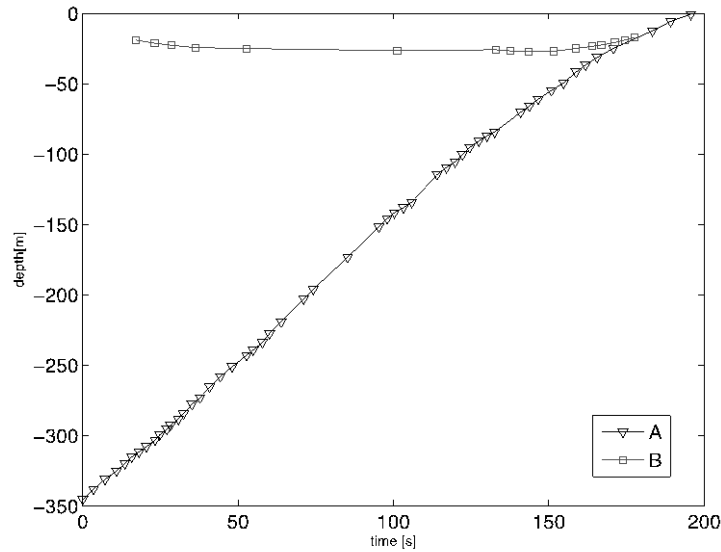
## RESULTS

As previously discussed, we developed a system model for a communication system, where the controller at the transmitter decides whether or not to attempt a transmission based on the dynamic programming solution. We do this for both cases, where the controller is only at the transmitter, and where the controller is also implemented at the receiver. In this latter case, the optimal policy minimizes the overall network (here two nodes) transmission (of data and feedback) attempts. The rationale behind this study is that for example, some energy could be saved by transmitting feedback less frequently, such as in case the channel memory is high. Results are shown in Fig. 1. The curve labeled as PNCCSI represents the ideal performance of the communication system, where a controller perfectly knows the CSI before transmitting. The curve labeled as BLIND, corresponds to the communication performance when no controller is implemented and it represents the worst case scenario. The curve labeled as PCCSI, represents the performance of the communication system with the controller proposed in the literature, where a perfect causal (with lag 1) CSI is always available at the transmitter, even when no packet is transmitted. When such delayed CSI is only available when a transmission is decided by the controller, the performance of that system degrades as shown by the curve labeled as PD-PCCSI-nocsi. Therefore, we propose a different model that takes into account the lag with which the CSI is known at the transmitter. The curve labeled as DP-PCCSI-lag represents the performance of the communication system with the proposed model. It can be noticed that its performance slightly degrades with respect to the PCCSI case, but in this case the feedback is transmitted only when a packet is sent. Note that in these curves we neglect the cost due to the feedback transmission. The curve DP-PCCSI-lag-csi indicates the performance obtained by the proposed controller and the CSI is transmitted at each stage as in PCCSI, and therefore it reaches equivalent performance of those obtained with the model in the literature.

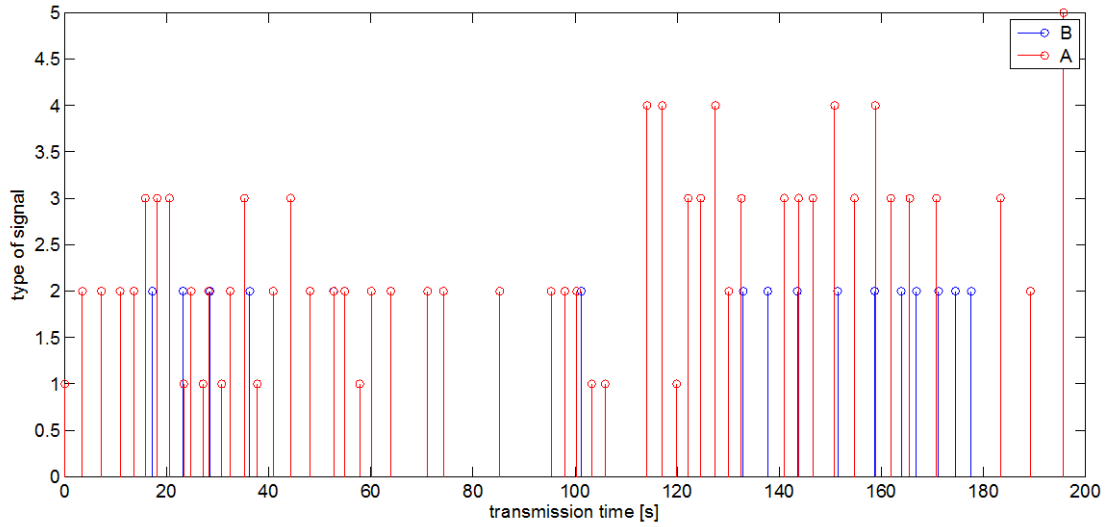


**Figure 1: Percentage,  $d$ , of successful transmissions over a period,  $T$ , as a function of average percentage of transmission attempts (called Normalized Transmission Cost (NTC)) performed in order to achieve  $d$ .**

Fig. 2 and 3 present the time series of the depth of the animals, transmission instants and type of signal transmitted from each animal, respectively. The type of signal follows a previous classification of stereotyped calls of pilot whales. Note that the animal ascending is also vocalizing more than the animal at the surface, which transmits always the same type of signal.



**Figure 2: Depth measured by the DTag for both pilot whales A (ascending from a deep dive) and B (staying at the surface) as a function of time.**



**Figure 3: Transmission time of animal A (in red), which is ascending from a deep dive, and animal B (in blue) staying at the surface. The y-axis represents the type of signal that was transmitted.**

## IMPACT/APPLICATIONS

In case all the goals are met, the outcome consists in having communication techniques that saves energy with different channel conditions. This corresponds to longer battery lifetime for any sensor that include a communication payload.

Moreover, a better knowledge on the pilot whales' communication paradigms and their multi-user interference management could inspire the design of better performing communication systems.

## RELATED PROJECTS

The PIs have also started to participate to the Multi-study Ocean acoustic Human effects Analysis (MOCHA) meetings, and collaborate with the involved scientists.